Electromagnetic Nondestructive Testing of Composite Materials

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Abstract: Today modern industry make very extensive use of various composite materials. Because of complexity of such structures, abilities of commonly used NDT methods sometimes are not sufficient. More advanced techniques should be utilized. In this paper T-Ray (terahertz radiation) method is presented for the purposes of various composite materials evaluation. Finite Element Method modeling of terahertz evaluation is shown and reconstruction procedure based on basic signal processing algorithms was proposed.

Keywords: Terahertz technique; Composite materials evaluation; Signal processing; Defect reconstruction
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复合材料电磁无损检测

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摘　要:各种复合材料广泛地使用于现代工业生产中。由于复合材料的复杂性,常规无损检测技术往往不再适用。对基于亚毫米波技术的复合材料检测技术作介绍。给出了有限元模型,并提出了基于简单信号处理算法的重构技术。

关键词:亚毫米波技术;复合材料检测;信号处理;缺陷重构

Because of high corrosion resistance, sufficient stiffness and high strength to weight ratio today modern industry make very extensive use of various composite materials. Composites occur in wind turbines, tanks, automotive, maritime and aeronautical constructions. Ultrasonics, eddy current method, microwave technique, optical methods and thermography are commonly used techniques for non-destructive testing (NDT) of composite materials[1]. Due to heterogeneous structure of composites (multi-layer nature and fiber waviness) the defects differs from those typically found in metals. Detection and identification of discontinuities is more complicated task in this case. Advanced NDT technique such as terahertz spectroscopy makes possible very precise characterization of defect location (high spatial resolution). Mentioned technique can be used to evaluate interior of layered composite laminates. In this paper T-Ray (terahertz radiation) method is utilized for evaluation of selected kinds of composite materials.

1　Terahertz technique in composites inspection

Terahertz electromagnetic radiation enables non-invasive, non-ionizing and non-contact examination of dielectric materials such as: plastics, dry wood, explosives ceramics, foams and composites - especially glass fiber reinforced. The T-Rays are sensitive for refractive index. Any defect which disturbs refractive index, eg, void, delamination, inclusion, material inhomogeneities (fiber/matrix distribution), surface roughness, fiber waviness and internal interfaces between layers (in layered structures), can be detected. In most cases, defects are located by reflection and transmission imaging based on pulsed terahertz TDS (Time Domain Spectroscopy)[2]. The method is well suited for evaluation of layered materials. Each interface between separate layers causes reflection of incident THz pulse and attenuation of transmitted one. Differences in delays of the propagated pulses and their echo (delayed layer reflections) enable characterization of the thicknesses and inner structure state. Very short pulses (order of picoseconds) contain wide frequency bandwidth (0.05 ～3 THz) and therefore it is possible to carry one single point broadband measurements.

The main components of THz TDS system are: pair of transducers (transmitter and receiver), ultra fast laser and optical delay line.

THz pulses are generated and picked up by photoconductive antennas(PCA)[3]. Simplified scheme of such device is shown in Figure 1. The main part of the THz transmitter is bowtie antenna with photoconductive gap, which is illuminated by femtosecond laser pulses. Such excitation and application of external DC bias causes pulsed current flow through metallic part of antenna. The currents induce electromagnetic wave. The resulting bowtie antenna radiation is collimated by high resistivity hemispherical silicon lens and then focused on examined object surface by High-Density PolyEthylene (HDPE) lens. Simplified block scheme of pulsed terahertz TDS system and a view of equipment applied during our measurements is presented in Figure 2. The TRay4000 imaging system from Picometrix offers the frequency resolution of 3 GHz and average power of THz beam - less than 500 W. Lateral resolution of

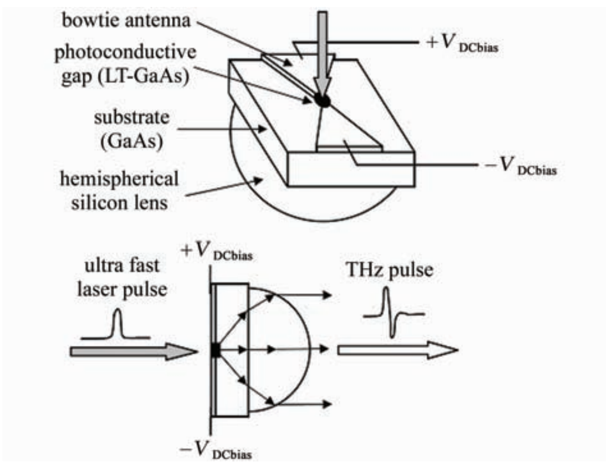


Fig. 1 THz photoconductive transmitter (PCA bowtie antenna)

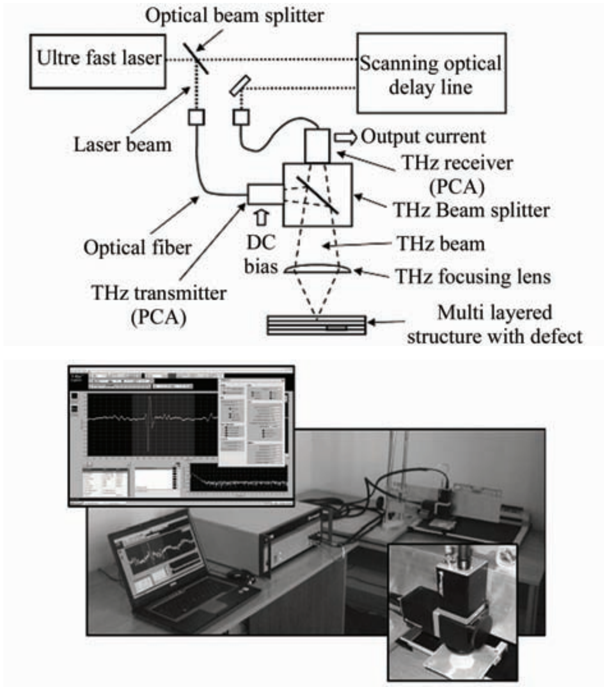


Fig. 2 Scheme and view of pulsed terahertz TDS system

TDS technique is less than 200 m and depth resolution is less than 50 m[4].

2 Experiment with FEM computations

Because of high computational effort and memory requirements (small wavelength of THz wave according to physical dimensions of applied devices and evaluated specimens) Finite Element Method is not an optimal tool for THz technique simulations. The model presented in Figure 3 is simplified (2 dimensions and dipole antenna instead of bowtie) and reduced in space, but consist of all parts of measuring head and further can be developed in order to optimize its construction. The numerical computations allow to calculate A-scan signals which are shown in Figure 3.

3 Results of THz TDS measurements and data analysis

Pulsed THz TDS is very well suited for non-destructive inspection of non-conducting composites. One of the most important information about fiber reinforced composite which can be gained using presented technique is fiber orientation and fiber/matrix distribution. An

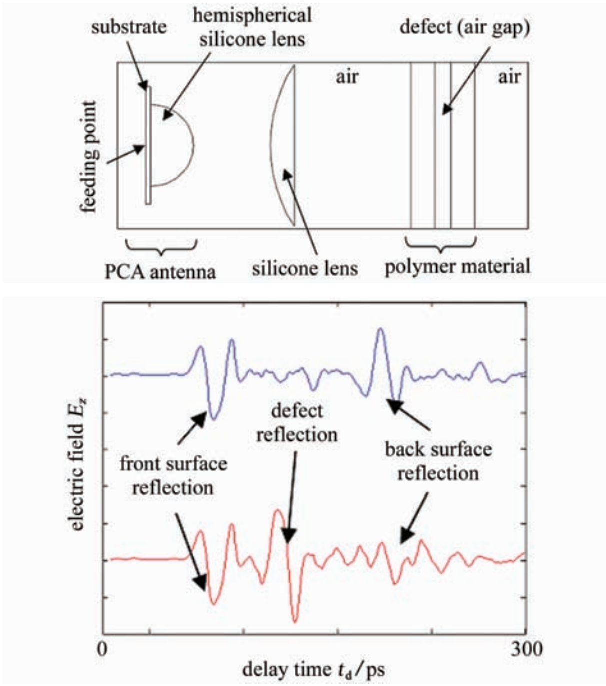
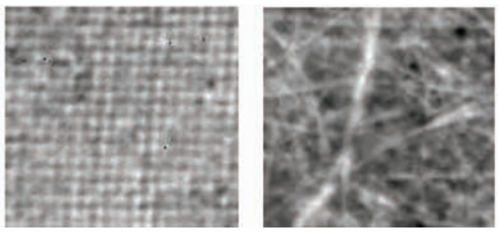


Fig. 3 Geometry of FEM numerical model and resulting A-scan signals



(a) regular fiber orientation (b) irregular fiber orientation

Fig. 4 C-Scan of various glass-fiber composite structures evaluation using terahertz TDS

exemplary C-scan signals obtained for regular and irregular fiber structures are shown in Figure 4. A B-scan signal obtained by reflection inspection of delaminated glass fiber reinforced composite using terahertz technique is shown in Figure 5. Mechanical damage (impact) was introduced to the examined specimen before testing procedure. Surface waviness and delamination between interior layers are easily detectable in resulting signal. Delamination is one of the most serious problem that can occur in laminates. It can affect structural integrity of material by reducing mechanical stiffness and compressive strength. That's why effective flaw detection procedure must be utilized. Block scheme of the flaw detection and reconstruction algorithm is presented in Figure 6. For each position (x, y) a measured signal is aligned in delay time domain in order to simplify further signal processing algorithms and reduce an influence of surface roughness. Signals are aligned to position of THz pulses' minimum. After that several time delay values (t_{d1}, t_{d2} and t_{d3}) are selected and corresponding C - scan signals are

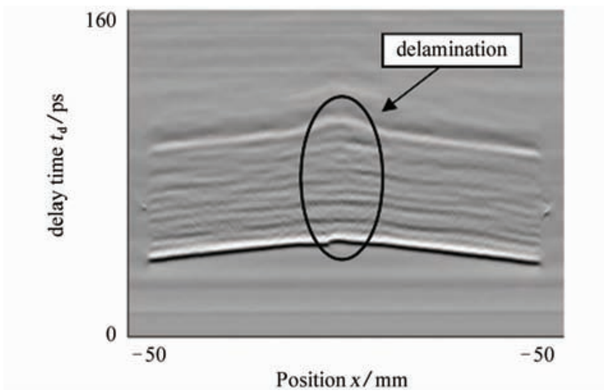


Fig. 5 B-scan of delaminated specimen

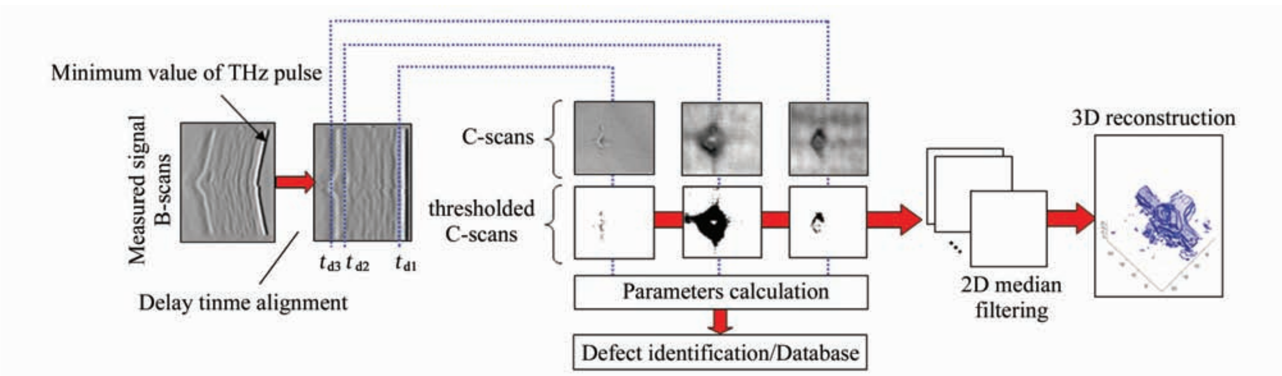


Fig. 6 Block scheme of defect detection and reconstruction algorithm

detrended and thresholded in order to detect areas with high probability of defect detection (POD). Next, thresholded C-scans are parameterized. Selected features like: defected area, shape coefficients and position - depth in examined specimen which corresponds to value of delay time t_{dn} are calculated.

On the basis of above-mentioned information, a database of defects' parameters is created. Future decisions about membership to specific class of flaws (eg, delamination, void, inclusion, etc) will be done using comparison with database records. Quality of classification depends on size of database, thus extensive atlas of possible defects will be prepared.

One can observe, the delamination profiles differ significantly depending on depth of examination, thus pulsed THz TDS method may be very effective tool in non-destructive evaluation of multilayered composite materials. More information about flaw profile can be gained using 3D reconstruction (Figure 6). Detrended and thresholded C-scan signals are filtered with 2D median filter. The threshold value is chosen for each C-scan based on mean, maximum and minimum value of signal. Achieved patterns are combined together. The third dimension z (along depth of the specimen) can be achieved using td information: $z=f(t_d)$. The view of delamination and resulting 3D reconstruction of defect is presented in Figure 7.

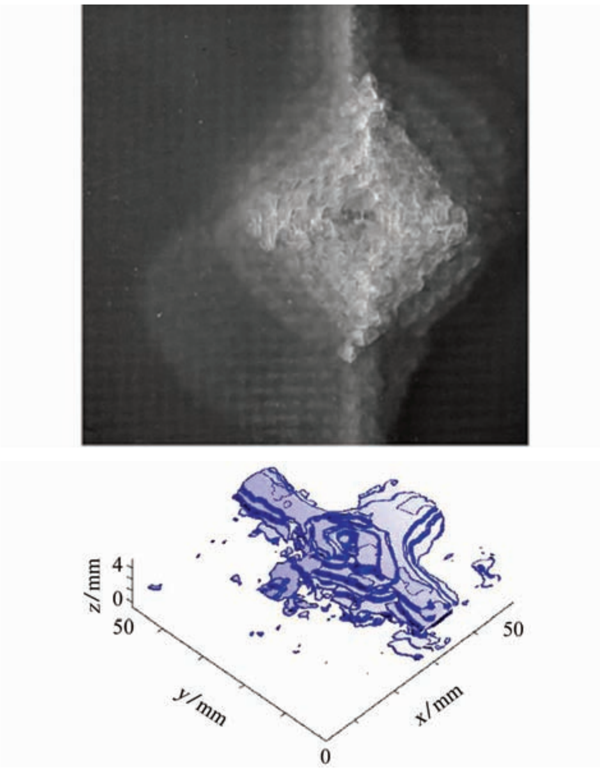


Fig. 7 Photo of delamination in glass-fiber laminate and result of its reconstruction

4 Conclusions

Pulsed terahertz time domain spectroscopy offers very wide abilities of inspection. It is sensitive for refractive index thus provide a lot of information about internal structure of evaluated dielectric materials. Proposed algorithm of defects' detection (Figure 6) may be very effective tool for non-destructive evaluation of multilayered composite materials. Both: parameters identification and 3D profile reconstruction can be achieved.

5 Acknowledgement

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